

What IceCube data tell us about neutrino emission from star-forming galaxies (so far)

Luis A. Anchordoqui,^{1,2} Thomas C. Paul,^{2,3} Luiz H. M. da Silva,² Diego F. Torres,^{4,5} and Brian J. Vlcek²

¹Department of Physics and Astronomy, Lehman College at CUNY, Bronx NY 10468, USA

²Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

³Department of Physics, Northeastern University, Boston, MA 02115, USA

⁴Institute of Space Sciences (IEEC-CSIC), Campus UAB, Torre C5, 2a planta, 08193 Barcelona, Spain

⁵Institució Catalana de Recerca i Estudis Avançats (ICREA), Spain

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Very recently, the IceCube Collaboration reported a flux of neutrinos in the energy range $50 \text{ TeV} \lesssim E_\nu \lesssim 2 \text{ PeV}$, which departs from expectations from atmospheric background at the 5.7σ level. This flux is in remarkable agreement with the expected diffuse flux of neutrinos from starburst galaxies, and the 3 highest energy events have uncertainty contours encompassing some of such systems. These events, all of which have well-measured energies above 1 PeV , exhibit shower topologies, for which the angular resolution is about 15° . Due to this angular uncertainty and the *a posteriori* nature of cuts used in our study it is not possible to assign a robust statistical significance to this association. Using muon tracks, which have angular resolution $< 1^\circ$, we compute the number of observations required to make a statistically significant statement, and show that in a few years of operation the upgraded IceCube detector should be able to confirm or refute this hypothesis. We also note that double bang topology rates constitute a possible discriminator among various astrophysical sources.

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In 2012, the IceCube Collaboration famously announced an observation of two $\sim 1 \text{ PeV}$ neutrinos discovered in a search for the expected cosmogenic neutrinos [1]. The search technique was refined to extend the neutrino sensitivity to lower energies [2], resulting in the discovery of an additional 26 neutrino candidates with energies between 50 TeV and 2 PeV , constituting a 4.1σ excess for the combined 28 events compared to expectations from neutrino and muon backgrounds generated in Earth's atmosphere [3]. Very recently, these results have been updated [4]. At the time of writing, 37 events have been reported in three years of IceCube data taking (988 days between 2010 – 2013). The data are consistent with expectations for equal fluxes of all three neutrino flavors and with isotropic arrival directions. Moreover, the next to highest energy event has equatorial coordinates ($\alpha = 38.3^\circ, \delta = -67.2^\circ$) and therefore cannot originate from the Galactic plane. Assuming a power law spectrum $\propto E_\nu^{-2}$, the three year data set is consistent with an astrophysical flux at the level of $3 \times 10^{-8} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, and rejects a purely atmospheric explanation at 5.7σ [4]. Herein we consider the issue of what the data reported so far may suggest regarding the possibility that the extraterrestrial neutrinos originate in star-forming regions [5].

Both the neutrino energy spectrum and directional measurements provide clues about which astrophysical sources may be responsible for extraterrestrial neutrinos. We will begin with a discussion of characteristics of the energy spectrum as it pertains to potential source candidates, and then move on to the issue of directional correlations with astrophysical objects. First, however, we should remind the reader that the three neutrino species ν_e , ν_μ and ν_τ induce different characteristic signal morphologies when they interact in ice

producing the Cherenkov light detected by the IceCube optical modules. The charged current (CC) interaction of ν_e produces an electromagnetic shower which ranges out quickly. Such a shower produces a rather symmetric signal, and hence exhibits a poor angular resolution of about $15^\circ - 20^\circ$ [3]. On the other hand, a fully or mostly contained shower event allows one to infer a relatively precise measurement of the ν_e energy, with a resolution of $\Delta(\log_{10} E_\nu) \approx 0.26$ [6]. The situation is reversed for ν_μ events. In this case, CC interaction in the ice generates a muon which travels relatively unhindered leaving behind a track. Tracks point nearly in the direction of the original ν_μ and thus provide good angular resolution of about 0.7° , while the “electromagnetic equivalent energy” deposited represents only a lower bound of the true ν_μ energy. The true energy may be up to a factor 10 larger than the observed electromagnetic equivalent energy. Finally, ν_τ CC interactions may, depending on the neutrino energy, produce “double bang” events [7], with one shower produced by the initial ν_τ collision in the ice, and the second shower resulting from most subsequent τ decays. Separation of the two bangs is feasible for ν_τ energies above about 3 PeV , while at lower energies the showers tend to overlap one another [8].

With these points in mind, we now move to the current state of the neutrino energy measurements. One striking feature of the IceCube spectrum is that, assuming an unbroken $E_\nu^{-\gamma}$, $\gamma = 2$ flux expected from Fermi acceleration in strong shocks, there is either a cutoff or a spectral break evident around 2 PeV . Notably, there is no increase in observation rate near 6.3 PeV , as one would expect from the Glashow resonance [9]. This implies that either the acceleration process dies out at some energy, or that the spectrum is simply steeper than $\gamma = 2$. It has been shown elsewhere that an unbroken power law

spectrum with $\gamma = 2.3$ is also reasonably consistent with the IceCube data [10].

In order to ascertain the physical processes which could underlie these spectral features, let us discuss briefly plausible neutrino production mechanisms. It is generally thought that extraterrestrial neutrinos are produced via proton interactions with either photons or gas near the proton acceleration sites, resulting in pions which in turn generate neutrinos as decay products. For the case of neutrino production via $p\gamma$ interactions, the center-of-momentum energy of the interaction must be sufficient to excite a Δ^+ resonance, the $\Delta^+(1232)$ having the largest cross-section. The threshold proton energy for neutrino production on a thermal photon background of average energy E_γ is

$$E_{\text{th}} = m_\pi(m_p + m_\pi/2)/E_\gamma, \quad (1)$$

where m_π and m_p are the masses of the pion and proton, respectively. Since the proton energy must be about 16 times higher than the daughter neutrino energies, Eq. (1) implies photons with energies in the range ~ 6 eV should be abundant in the region of proton acceleration in order to generate \sim PeV neutrinos. Gamma-ray bursts (GRBs) may be the only astrophysical objects capable of generating a photon background of the required energy for this scenario [11]. Furthermore, production of neutrinos in the 100 TeV range requires photon energies about an order of magnitude higher. In contrast, if neutrinos are produced via interaction in gas near the acceleration site, the energy threshold requirement is lifted, as pp interactions generate pions over a broad range of energies.

Extending previous multifrequency studies of individual galaxies [13], Loeb and Waxman (LW) [14] showed in 2006 that starburst galaxies constitute a compelling source for efficient neutrino production up to ~ 0.3 PeV, and possibly beyond, though for energies exceeding 1 PeV the predictions are quite uncertain. For energies up to ~ 1 PeV, the LW analysis predicts a spectral index $\gamma = 2.15 \pm 0.10$ which accurately fits the IceCube data, and indeed predicts an observation rate for E_ν of $10^{1.5 \pm 0.05}$ for a 1 km³ detector, in line with the rate subsequently observed by IceCube. Neutrino production from π^\pm decays must be accompanied by a corresponding flux of gamma rays from decays of π^0 's produced in the pp interactions, providing a robust cross-check of the pion production rate and corresponding neutrino spectrum. A spectrum steeper than $\gamma \sim 2.2$ leads to an overproduction of gamma rays compared to measurements by Fermi-LAT [15], indicating that a soft unbroken $\gamma = 2.3$ spectrum is implausible for extragalactic sources. Thus, it seems that a cutoff or suppression must be at play. All in all, the starburst source hypothesis together with a steepening of the spectrum to at least $\gamma = 3.75$ above 3 PeV fits well to the IceCube data and satisfies the constraints from gamma ray observations, as shown in Fig. 1.

We now discuss how double bang topologies may serve as a discriminator among possible astrophysical

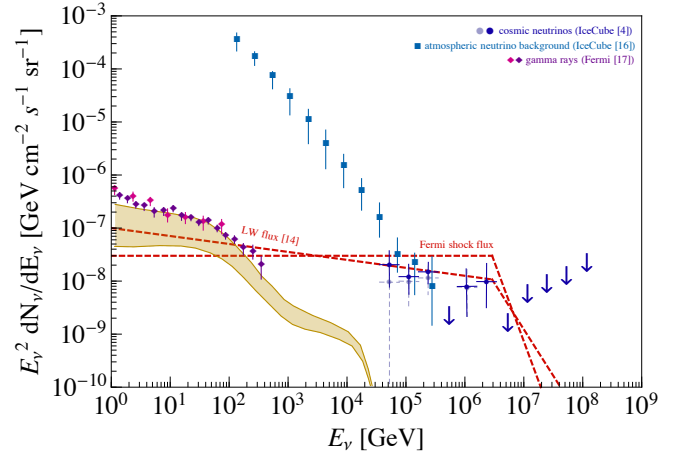
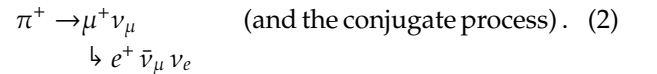


FIG. 1. Neutrino and gamma ray spectra compared to two neutrino spectral indices. The squares show the background from atmospheric ν_μ events as observed by IceCube40 [16]. The circles and arrows show the recently reported IceCube flux (points with solid error bars do not include prompt background while those with dash error bars do) [4]. The diamonds are gamma ray flux measurements from Fermi [17]. The two dashed lines correspond to $E_\nu^2 dN_\nu/dE_\nu = 10^{-7} E_\nu^{-0.15}$ GeV cm⁻² s⁻¹ sr⁻¹ and $E_\nu^2 dN_\nu/dE_\nu = 3 \times 10^{-8}$ GeV cm⁻² s⁻¹ sr⁻¹, with the spectrum steepening above about 2 PeV to $\gamma = 3.75$ and $\gamma = 5.0$, respectively. For these two neutrino fluxes, the associated predictions for the gamma ray fluxes after propagation are displayed as the upper and lower bounds of the shaded region [15]. Note that the spectral index $\gamma = 2.15$ at injection agrees well with both the Fermi-LAT and IceCube measurements.

sources powered by highly relativistic winds. Extraterrestrial neutrino production proceeds via the decay chain



This decay chain may be complete in the sense that both decays indicated in Eq. (2) occur without significant change in the μ energy, or it may be incomplete, in which case the μ suffers possibly catastrophic energy loss before decay. For the case of a complete decay chain, each neutrino carries on average about 1/4 of the parent pion energy. If the μ radiates away energy before it decays, the ν_μ from the first decay will still carry on average 1/4 of the π^\pm energy, while the other two neutrinos will emerge with less than the nominal 1/4 of the parent pion energy. In such a scenario it is conceivable that the first ν_μ in the chain can be produced above 3 PeV, whereas $\bar{\nu}_e$ may not reach beyond 2 PeV, and in particular may not be able to reach the energy required to interact at the Glashow resonance.

We now discuss the muon energy loss quantitatively by exploiting the observation of gamma rays accompanying the neutrino flux. In the case of muons with energies in excess of 1 PeV, energy losses are dominated by synchrotron radiation. The synchrotron loss time is determined by the energy density of the mag-

netic field in the wind rest frame. Defining $\tau_{\mu,\text{syn}}$ as the characteristic muon cooling time via synchrotron radiation and $\tau_{\mu,\text{decay}}$ as the muon decay time, it is necessary that $\tau_{\mu,\text{syn}} < \tau_{\mu,\text{decay}}$ in order for the decay chain to be complete. $\tau_{\mu,\text{syn}} \sim \tau_{\mu,\text{decay}}$ determines a critical energy E_{μ}^{syn} at which energy losses begin to affect the decay chain. For the characteristic parameters of a GRB wind, the maximum energy at which all neutrinos in the decay chain have on average 1/4 of the pion energy is

$$E_{\nu}^{\text{syn}} \approx \frac{1}{3} E_{\mu}^{\text{syn}} \sim \frac{1}{3} \frac{\Gamma_{2.5}^4 \Delta t_{-3}}{L_{52}^{1/2}} \text{ PeV}, \quad (3)$$

where $\Gamma = 10^{2.5} \Gamma_{2.5}$ is the wind Lorentz factor, $L = 10^{52} L_{52}$ erg/s is the kinetic energy luminosity of the wind, and $\Delta t = 10^3 \Delta t_{-3}$ s is the observed variability time scale of the gamma-ray signal [18]. Equation 3 is also valid for neutrinos produced in blazars. In this case, $\Delta t \sim 10^4$ s, $\Gamma \sim 10$, and $L \sim 10^{47}$ erg/s, yielding $E_{\nu}^{\text{syn}} \sim 1$ EeV. For starbursts, the galactic wind is non-relativistic and the magnetic field is small enough to render synchrotron losses negligible in comparison. In summary, for GRBs, the muon cooling is sufficient to influence the decay chain in such a way as to affect the flavor ratios at PeV energies, whereas for blazar and starbursts the decay chain is only affected for muon energies $\gg 10$ PeV. Note that for GRBs, $\Delta t_{-3} \sim 1$ constitutes a lower bound, and hence the consequences discussed herein may require some fine-tuning of the parameters of Eq. (3).

It is nonetheless worth noting some potential consequences of the above hypotheses. As noted elsewhere $p\gamma$ interactions produce fewer $\bar{\nu}_e$ than pp interactions [19]. Indeed, most of the $\bar{\nu}_e$ flux originates via oscillations of $\bar{\nu}_\mu$ produced via μ^+ decay. For production of $E_{\nu} \gtrsim 1$ PeV in GRBs, the ν_μ in the chain of Eq. (2) is more energetic than the $\bar{\nu}_\mu$. This may suggest that the softening of the spectral index takes place at different energies for neutrino and antineutrino fluxes. If this were the case, at production the high energy end of the GRB flux would be dominated by ν_μ produced via π^+ decay. As described previously, however, IceCube can measure only lower bounds for the muon energies. As it turns out, IceCube has recently recorded a ν_μ with a minimum energy of 0.5 PeV [20], but which may have an energy as much as 10 times higher. If this is indeed the case, it could indicate a high energy muon from the first decay of Eq. (2). We can also speculate on more potentially convincing observations which may emerge in the future. Assuming maximal $\nu_\mu - \nu_\tau$ mixing, observation of a high energy ν_μ may imply eventual observation of a high energy ν_τ , which above about 3 PeV would exhibit the distinctive double bang topology discussed above. Note that some fine tuning of the model presented here may be required for such events to manifest. In particular, the μ^\pm cooling time of Eq. (3) must be smaller than the μ^\pm decay time in order to prevent the $\bar{\nu}_e$ from reaching the Glashow resonance (thus far not observed). Further, the π^\pm cooling time must exceed its lifetime in order to produce a ν_τ

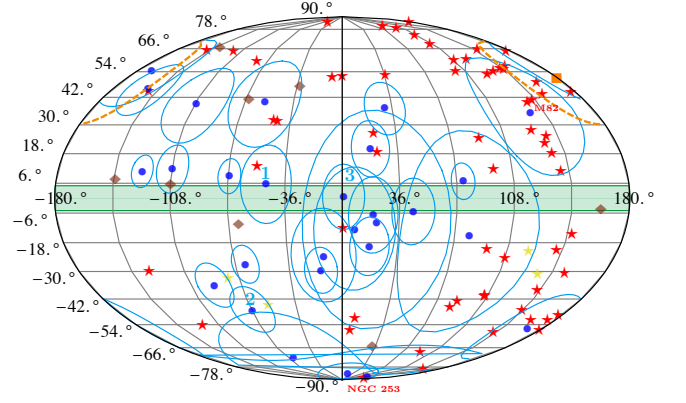


FIG. 2. Comparison of IceCube event locations [4] with star-forming galaxies [22] and the ultrahigh energy cosmic ray hot-spot reported by the TA Collaboration [27] in a Mollweide projection. The 27 shower events (circles) and 8 track events (diamonds) reported by the IceCube Collaboration. The 3 highest energy events are labeled 1, 2, 3, from high to low, respectively. The red stars indicate the 64 star-forming galaxies beyond the Local Group. The 4 yellow stars indicate galaxies in the local group. NGC 253 and M82, our two closest starbursts, are labeled. The shaded band delimits the Galactic plane. The square in the upper right marks the center of the TA hot-spot, with the surrounding dashed line indicating its 20° extent.

above ~ 3 PeV. Further, as this is a phenomenological exercise, we have neglected possible experimental effects. As such, this study is not meant to make a concrete prediction, but rather to point out that *if* such double bang topologies are observed in the future while the Glashow resonance is not, it would provide a valuable piece to the puzzle of extraterrestrial neutrino origins, favoring the GRB hypothesis over the blazar or starburst ones, each of which would require implausible fine-tuning to be consistent with observation.

Now, since starburst galaxies are plausible source candidates, consistent with the neutrino energetics observed so far, the next obvious step is to check whether there are any correlations with the positions of starburst galaxies and the observed neutrino arrival directions. Before proceeding we note that hypernovae, which may well be responsible for sub-PeV to PeV neutrino emissions [21], are present in starburst galaxies as well as other star forming regions, though the rate of occurrence is higher in starburst galaxies. To test the hypothesis that star forming regions correlate with the IceCube events, we have employed the list of star-forming regions compiled by the Fermi-LAT Collaboration [22], which includes 64 of the 65 sources of the HCN survey [23] as well as the local galaxies (SMC, LMC, M31, and M33). The HCN survey is, to date, the most complete study of galaxies with dense molecular gas content. It includes nearly all the IR-bright galaxies in the northern sky ($\delta \geq -35^\circ$) with strong CO emission, as well as additional galaxies taken from other surveys. Objects within the Galactic latitudes $|b| < 10^\circ$ are not included in the survey due to

diffuse emission from the Galactic plane.

A comparison among all of the IceCube events and the star-forming galaxy survey is shown in Fig. 2. Not surprisingly given the size of the localization error, there are a few coincidences, among them the two nearby starbursts M82 and NGC 253 (observed in gamma-rays [24, 25] which are considered to be possible ultrahigh energy cosmic ray emitters [26]). The highest energy event correlates with NGC 4945, the second highest with the SMC, and the third highest correlates with IRAS 18293-3413. However, none of the track topologies correlates with an object in the survey.

To estimate the number of ν_μ required to make a statistically significant statement, we have run 10^6 simulations with 68 sources and computed the fraction correlating by chance with 1° circular regions of the sky. Of these, 90% of the simulations show 0 correlations. If future observations contain 5 or more ν_μ events which correlate with the 68 sources in the survey, an association by chance will be excluded at more than 99% CL [28].

For ν_μ events, the equivalent electromagnetic energy represents only a lower bound on the true neutrino energy. Consequently, escaping the background region requires setting a cut on the electromagnetic equivalent energy ≈ 0.5 PeV. This threshold is arrived at via the following argument. Figure 1 shows that at $E_\nu = 1$ PeV the background from prompt emission is negligible. Since

the muon neutrino energy is at least 2 times the inferred electromagnetic equivalent energy, the proposed cut produces a virtually background-free sample. Since 1 such event has already been recorded, we might guess an observation rate of 1 event every ~ 2 years, indicating a long wait with the current 1 km^3 configuration. Next generation IceCube, which could increase the instrumented volume by up to an order of magnitude (but with larger string spacing), will therefore be greatly beneficial for this study, as well as other correlation analyses.

We conclude with one additional observation. It was recently noted [29] that the ultrahigh energy cosmic ray hot-spot reported by the TA Collaboration [27] correlates with 2 of the 28 events initially reported by the IceCube Collaboration [3], with a statistical significance of around 2σ . In the newer IceCube data (the 37 event sample [4]) there is one additional shower event which correlates with the TA hot-spot, as shown in Fig 2. The hot-spot also contains an abundance of star-forming regions and is near M82.

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